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Laser cleaning of mirror surface for optical diagnostic systems of the ITER

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Abstract

The development of cleaning optics and deposition-mitigating techniques is a key factor in the construction and operation of optical diagnostics in ITER. The cleaning of optical surface by pulsed radiation from a fiber laser is an effective method that can recover optical properties of the mirror surface. The possibility of cleaning metallic mirrors from films with complex composition by pulsed radiation from a fiber laser has been experimentally researched. It has been shown that high initial reflection characteristics of optical elements can be recovered by choosing regimes of radiation effect on the deposited surface. Efficient cleaning is ensured by radiation with the power density of less than 10^7 W/cm². At this relatively low power density, pollutions are removed in a solid phase and the thermal effect on the mirror is insignificant. Preliminary experiments of the metal mirrors cleaning by fiber laser radiation have demonstrated the possibility of hardware implementation techniques. Experiments on transport of laser radiation to the metal mirror by using a system of lens and cleaning showed the possibility of a hardware implementation of methods applicable in the geometry of the port-plug ITER.

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1. Introduction

In the fusion reactor ITER it is supposed to use a complex of the optical diagnostics measuring plasma characteristics. Optical elements of diagnostic systems located within the reactor vacuum chamber are exposed to the intensive radiation effect, sputtering of the recharge atoms and contamination due to redeposit ion of sputtered materials of the first wall, limiters, divertor tiles and other elements. The most vulnerable element of optical systems is the first mirror, working surface of which faces plasma in the reactor chamber.

Experimental studies on the mirrors exposure carried out in tokamaks T-10 [Vukolov et al. (2004)], «Tore-Supra», TEXTOR [Lipa et al. (2006)], DIII-D [Rudakov et al. (2008)] and JET [Ivanova et al. (2008)] have shown, that the greatest change in the mirrors reflectance causes the deposited films of complex composition. Similar contamination of the first mirror surface leads to considerable decrease of its working life. Properties of the contaminated surface of an optical element depend on various conditions of the film formation: temperature, interaction time, composition of erosion products and gas in the plasma chamber, as well as material of a mirror and quality of its surface. The deposition of even thin (10-100 nm) transparent films on the metal mirrors can lead to spectral distortions in the reflected radiation because of the interference effects. Replacement of mirrors in the tokamak ITER is practically impossible. Therefore there is necessity in development of the effective noncontact and distant methods of film removal, allowing to clean the mirror surface between operating cycles without depressurization of a chamber and dismantling of the optical elements.

In the paper the results of the cleaning effectiveness of metal mirrors (SS316 and Mo) from contaminating films of complex composition with using of pulsed laser radiation are presented.

2. Experimental apparatus and procedure of films cleaning

Experiments were performed using ytterbium fiber laser YLPM-1-4x200-20-20 (IPG Photonics). Laser wavelength is 1064 nm, mean output power up to 20 W, peak power up to 100 kW, pulse duration 4-200 ns, pulse repetition frequency up to 1 MHz. Two-axis galvanometer Coordinate Scanning Device was used for scanning of the samples surface by laser beam.

After Coordinate Scanning Device the objective is installed, allowing to obtain in the image plane the spot with the diameter ~ 50 microns at a distance of 850 mm. The optical scanning system allows to process 300 x 300 mm surface. The samples of mirrors made of molybdenum (Mo) and stainless steel (SS316) have been subjected to laser cleaning. Films of various compositions were deposited on the mirrors (Fig.1).

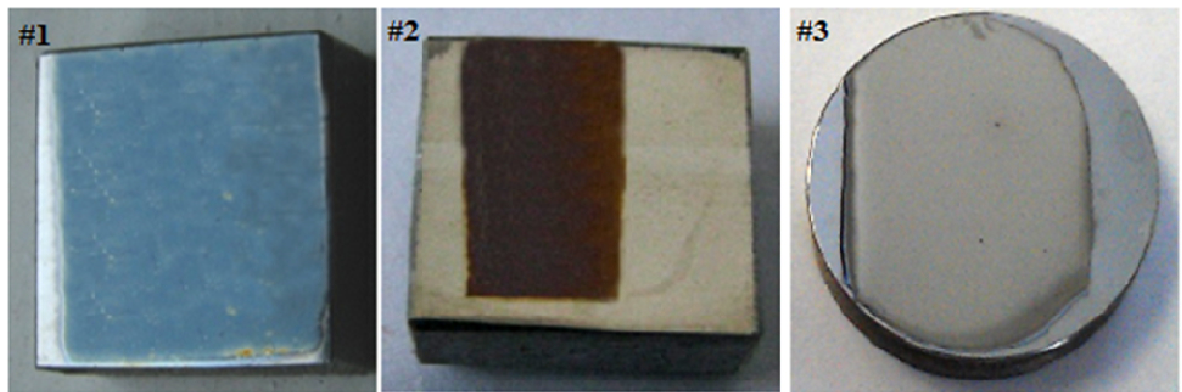


Fig. 1. Mirror samples with the films deposited in the T-10 tokamak #1, magnetron #2 and plasma #3.

The sample # 1 (material Mo, dimensions 10x10x4 mm, film thickness 110 nm) was exposed in the Tokamak T-10 chamber [Arkhipov et al. (2013)] (working gas D₂, gas composition D/D+C (30-40 %), 300 impulses by duration 1 sec). Sample # 2 (material SS316, dimensions 10x10x4 mm, film thickness 150 nm) was prepared by method of

magnetron sputtering [Vukolov et al. (2008)]. Deposition of films was performed in the conditions of working mixture containing 40% argon, 55% deuterium and 5% CHD₃. Film deposition duration was 120 min at temperature 120 °C. As a result, the carbon amorphous polymeric films a-C: H were deposited on the samples # 1, 2. In connection with proposed change of the first wall material for ITER with graphite on beryllium, as deposited material for sample #3 (material Mo, size 15 x 4 mm, film thickness 400 nm) was selected aluminum, as the most similar on physical and chemical properties to beryllium. The deposition of aluminum was carried out by plasma deposition [Begrambekov et al. (2008)] in argon atmosphere at pressure $1 \cdot 10^{-1}$ Pa, the residual gas pressure $2 \cdot 10^{-3}$ Pa. Discharge current on the aluminum target is 12 mA, the voltage at a target is 900V, mirror temperature 150°C. Deposition time is 7 min. Cleaning of mirrors was carried out in tracks 1 mm wide over the entire width of samples (with capture of clean metal surface).

3. Results and discussion

The power density at laser cleaning on various areas was varied in the range of 1 - 6 MW/cm². The pulse duration was 80 ns, the pulse repetition frequency 100 kHz. Laser beam scanned across the sample surface at rate of 2 m/s and with line spacing in 30 μm. Best results on cleaning were obtained at 4 MW/cm². Removal of contaminated films at relatively low power occurs in solid phase; therefore thermal effect on a mirror is inappreciable. Measurement of the mirror surface relief has shown the roughness decrease after cleaning in comparison with the original surface (Rz of source material is 25 nm, after cleaning is 15 nm), due to effect of laser polishing and can afford to restore the mirror surface, degraded during operation in the ITER. Regimes of cleaning of the sample #2 were practically the same. The spectral dependences characterizing a metal, a film and cleaned area of the mirror samples #1 (Mo) and #2 (SS) are presented in Fig. 2. The graphs show that surface quality is almost completely recovered.

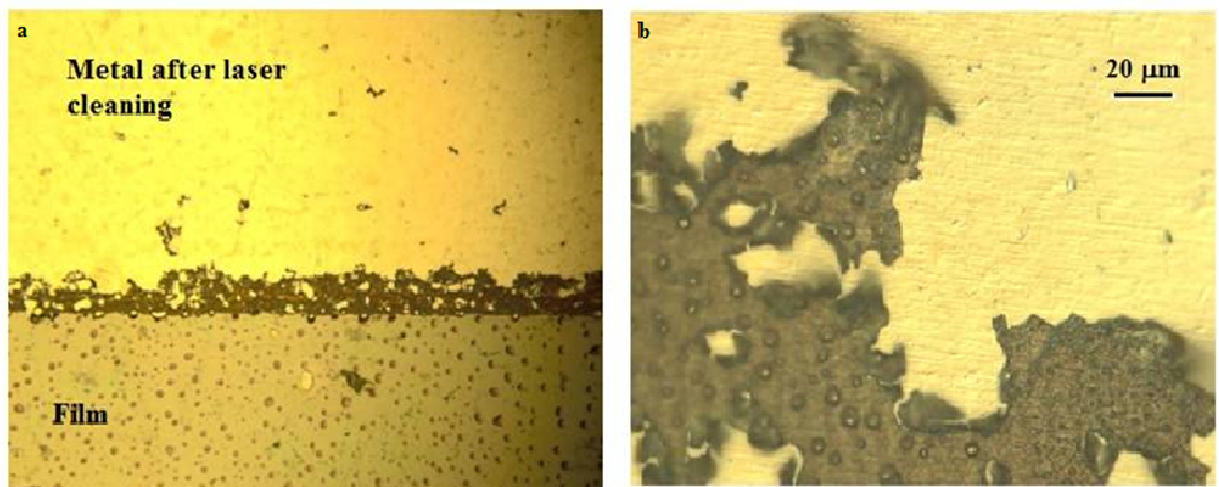


Fig. 2. Photo of sample # 2 after laser cleaning on the boundary of film and cleaned area (a) and area of the mirror surface with flaked film (b).

Regimes of removal of metal films differed essentially from cleaning of the hydrocarbon films. Multipass regimes with less pulsed power were more optimal. Thus, a mirror completely cleaned after 10 - 30 passes when using radiation with power density in 1 MW/cm². Herewith, at the same power in the case of using an impulse of less duration, the cleaning efficiency increases. Contaminated film from mirror surface was removed completely without damaging of the mirror material (Fig.3a). Examination of cleaning quality at the optical microscope have shown that after 10 passes on a surface the areas begin to form, in which the film flaking occurs (Fig.3b).

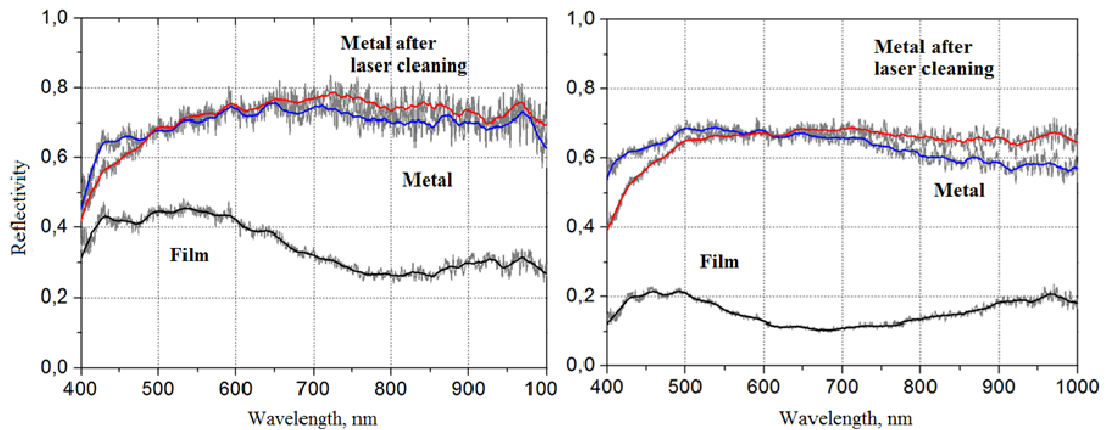


Fig. 3. Photo of sample # 2 after laser cleaning on the boundary of film and cleaned area (a) and area of the mirror surface with flaked film (b).

Complete removal of flaked areas was attained by several passes with the power reduced in 2 times.

Diagnostics, located in port-plugs ITER, will experience exposure to high radiation and neutron flux, strong magnetic fields (of the order of 1 Tesla). For this reason you cannot install a laser scanning system directly in a vacuum chamber port-plug diagnostic “Charge Exchange Recombination Spectroscopy” [Krupin et al. (2013)], and direct supply of laser radiation to the most polluted element of this diagnostic - the first mirror. For transportation of radiation to the first mirror geometry of ITER was created by the lens system (Fig. 4). This system consists of three lenses: one focusing and two forming a telescopic system with 1:1 magnification. Each of the telescopic lens system has a diameter of 182 mm. This allows scanning the surface 200x100 mm (the size of the first mirror is equal to this) at a distance of the depth of the port-plug ITER and the location of the mirror (3,5 m from the scanner).

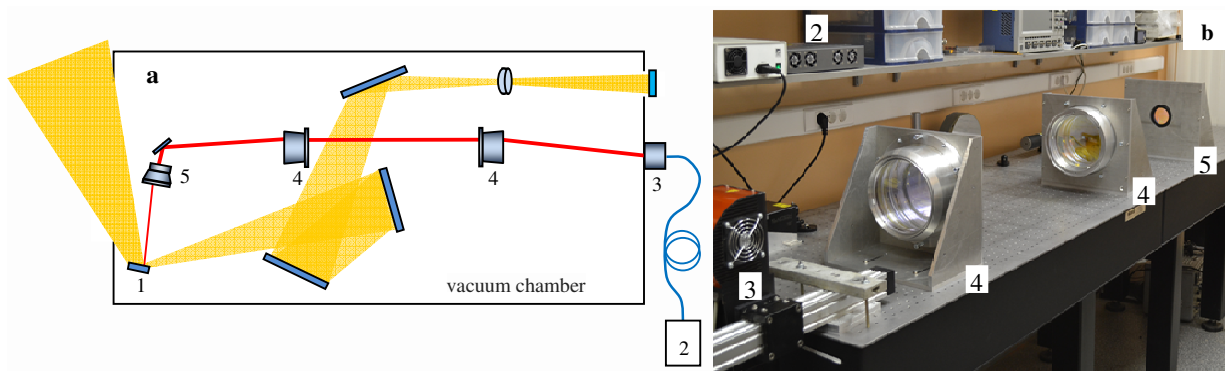


Fig. 4. The scheme of the transportation system in port-plug Charge Exchange Recombination Spectroscopy (a) and the prototype of the lens system of transportation on optical table (b). 1- the first mirror, 2- ytterbium fiber laser, 3- 2D scanner, 4 – the telescopic system, 5 - the focusing lens

The maximum achievable power density in the focus plane is tens of GW/cm^2 . This is 3 orders of magnitude higher than value required to remove films of complex composition.

4. Conclusions

The results of experimental researches devoted to possibility of metal mirror cleaning from the films of complex composition by pulsed radiation of fiber laser are presented. It is shown that selection of radiation effect regimes on

the surface with deposited film can be recover to initial reflective characteristics of metal mirrors. The effective cleaning is realized by radiation with power density less than 10^7 W/cm^2 . At such relatively low power density the contamination removal occurs in the solid phase therefore thermal effect on a mirror appears inappreciable. We have created a system of transportation of radiation applied in the geometry of the port-plug diagnostics “Charge Exchange Recombination Spectroscopy”. This system allows reaching in the treatment area power density required to remove films of complex composition.

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